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Subject: Emission Factors for Medical Waste Incinerators (MWI's)
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I. Introduction

The purpose of this memorandum is to document the methodology used to develop emission factors for MWI's. The emission factors are expressed in terms of pounds of pollutant emitted per pound of waste burned (lb/lb factors). These lb/lb factors will be used to calculate nationwide environmental impacts.

Section II of this memorandum describes the features of four alternative approaches that could be used to develop emission factors. Section II also shows the test data that were used to develop the factors. Section III describes the rationale for selecting one of these approaches and presents the resulting emission factors that were developed using the selected approach. Section IV lists the references.

II. Alternative Approaches for Developing Emission Factors

Four approaches were evaluated, all of which involve three general steps: (1) development of exhaust gas flow rate-to-waste burned factors (ft^3/lb factors), (2) development of pollutant concentrations for four types of control technologies, and (3) calculation of lb/lb factors by multiplying together the results of the first two steps.

The control technologies for which emission factors were developed are: combustion controls, wet scrubbers, dry scrubbers without carbon, and dry scrubbers with carbon. The exhaust gas flow rates, waste charging rates, and pollutant concentrations in each approach are from various MWI emissions tests. Table 1 shows all of the exhaust gas flow rates and waste charging rates from these tests.[1-32] Table 1 also shows the calculated ft^3/lb factors for each test run. Pollutant concentrations for each control technology are shown in Table 2. The methodology used to develop these concentrations is described in separate memoranda.[33-35]

The remainder of this section describes the four alternative approaches. Approaches A, B, and C were rejected, and approach D was selected. The reasons for selecting approach D and rejecting the others are presented in Section III.

A. <u>Approach A</u>

The first approach would rely on (1) information from tests of continuous MWI's to develop an average ft^3/lb factor and (2) pollutant concentrations from tests of both intermittent and continuous MWI's. Both the ft^3/lb factor and the pollutant concentrations would be based on giving each test run equal weight.

Only continuous data would be used to develop an average ft^3/lb factor because the relationship between the exhaust gas flow rate and the amount of waste burned is known only for continuous MWI's. For intermittent MWI's, the burning rate is an unknown fraction of the known charging rate.

The average pollutant concentrations would be based on data from both intermittent and continuous MWI's because the concentrations should be the same for both types of MWI's under similar operating conditions. After correcting the concentrations to seven percent oxygen, they should be the same for both types of MWI's, assuming the ratio of natural gas burned to waste burned is the same. This assumption should be reasonable when the primary chamber temperatures and configurations (e.g., the air distribution system) are the same.

B. <u>Approach B</u>

The second approach would be based entirely on data from continuous MWI's. In this case, average ft^3/lb factors would be developed for each of the tested MWI's. In addition, the actual pollutant emission concentrations (at 7 percent oxygen) for these MWI's would be used. The concentrations for each run in a particular test would be multiplied by the average ft^3/lb factor for that test to develop lb/lb factors for each test run. Average lb/lb factors for each pollutant and each control device would then be determined from the run-by-run data. Under this approach, data for each facility, rather than each run, are given equal weight.

Only one available test of a continuous MWI contains emission data for combustion controls, and this combustion control test has no Hg data. Dry scrubbers without carbon have been shown to have no effect on Hg emissions. Therefore, the Hg lb/lb factor for combustion control would be assumed to be the same as the factor for dry scrubbers without carbon.

C. Approach C

The third approach is similar to the approach B in two ways. First, the lb/lb factors for a particular control technology are based only on data from MWI's with that technology. In effect, different ft^3/lb factors are used for each control technology. Second, data from each facility, rather than each run, are given equal weight. This approach differs from approach B because data from both continuous and intermittent MWI's would be evaluated. By including intermittent data, the lack of combustion control data under approach B is not a problem in this case.

D. Approach D

The fourth approach is similar to approach A except that data from both continuous and intermittent MWI's would be used to calculate the average ft^3/lb factor. As in approach A, each run is given equal weight in developing the average ft^3/lb factor and pollutant concentrations. In this approach, the average ft^3/lb factor also is weighted based on the distribution of test runs for intermittent and continuous MWI's. This distribution may differ from the nationwide distribution of existing MWI's.

During emissions tests, the waste charging rates are recorded. For continuous MWI's the charging rate is equal to the burning rate, but for intermittent MWI's, the charging rate is greater than the burning rate. Thus, the burning rates in the tested intermittent MWI's had to be estimated before calculating the ft^3/lb factors. Burning rates were estimated using information from two incinerator manufacturers that presented rated waste charging capacities for continuous MWI's operated one shift per day versus continuous operation. The one shift operation can be assumed to characterize charging of intermittent MWI's at their design capacity. The charging rate for continuous operation can be assumed to characterize the true burning rate in such an intermittent MWI. (Tested MWI's were assumed to be operated at their design capacity.) One manufacturer indicated that the burn rate is equal to about 80 percent of the one-shift charging rate, and the other manufacturer indicated it is about 67 percent.[36,37] Thus, for this analysis, the burning rates for the tested intermittent MWI's were estimated to be equal to 70 percent of the reported charging rates.

Examination of the data in Table 1 shows the ft^3/lb factors are higher for intermittent MWI's than for continuous MWI's. This is true even when the actual charging rates, instead of the estimated burning rates, are used in the calculations. This result is unexpected. If the average waste characteristics and excess air levels are equivalent in all MWI's, using the waste charging rate should result in a lower ft^3/lb factor for intermittent MWI's than for continuous MWI's. Other design and operating characteristics also may contribute to this expected difference in ft^3/lb factors. For example, most existing continuous MWI's operate with higher SC temperatures (although this may not be true when compared with new intermittent MWI's, and we do not know the temperatures for the tested MWI's). To reach and maintain these higher temperatures would require more natural gas. A system that burns more natural gas would have a higher exhaust gas flow rate when corrected to seven percent oxygen. In addition, the continuous MWI's tend to have larger secondary chambers, which again suggests they would need more natural gas in the SC to maintain the temperature for a longer time.

As noted above, despite these expectations, the data in Table 1 show a higher ft^3/lb factor for the intermittent MWI's. This result suggests other parameters have not been considered. Perhaps the excess air level is higher in the intermittent MWI's than in continuous MWI's. This would lead to higher natural gas consumption to heat the extra air. Unfortunately, data on auxiliary fuel consumption rates are unavailable.

Alternatively, perhaps the assumption that the average waste heating values are identical is false. For example, maybe waste in intermittent MWI's, which are onsite, tends to be wetter than waste in continuous MWI's, which are often commercial facilities. The higher moisture content of the onsite waste would require more fuel to vaporize the water (if high enough, it also might reduce the maximum waste charging rate). Maybe water sprays are activated more frequently in intermittent MWI's to control temperature spikes.

Even if the moisture content is the same, another possible factor is that all of the boxes used to contain waste sent to commercial facilities slightly lowers the average heating value of the waste. Thus, the maximum charging rate could be higher for a given heat output (and air flow rate), effectively lowering the ft^3/lb factor for the commercial facility.

By using data from both continuous and intermittent MWI's, this approach has advantages over the approach A. First, it accounts for potentially real differences between intermittent and continuous MWI's. Second, even if there is no real difference in ft^3/lb factors for intermittent and continuous MWI's, this approach minimizes the effect of biases in either the continuous or intermittent data.

III. Selected Approach

Emission factors were estimated using approach D. Approaches B and C were rejected because the lb/lb factors are based on separate ft^3/lb factors for each control device rather than an overall average factor (there is no reason the ft^3/lb factors should vary by control device). Approach B was also rejected because of the lack of combustion control emissions data for continuous MWI's. Approach A is very similar to approach D because the average ft^3/lb factor for continuous MWI's is only slightly lower than the factor for all MWI's (2.27 vs. 2.67). As shown in Table 1, the factors for continuous and intermittent MWI's both vary over wide ranges, and the two ranges overlap. Because it is not clear what causes the variability or if one range (or both) is biased, using the average of all data is believed to be the most appropriate strategy. Therefore, emission factors were estimated using approach D. The resulting emission factors are presented in Table 3.

The general form of the equation used to calculate the lb/lb factors for pollutants with concentrations in ppm is given below:

$$EF = (R) \times (60\ \text{min/hr}) \times (C/10^6) \times (\text{lbmole}/385\ \text{dscf}) \times (MW)$$

where:

EF = pollutant emission factor, lb pollutant/lb waste charged
R = ratio of exhaust gas flow rate-to-waste charged, dscfm per lb waste charged per hour [used R = 2.67]
C = average concentration of pollutant, ppm
MW = molecular weight of pollutant, lb/lbmole

For example, the HCl emission factor for combustion control is calculated with R = 2.67, an HCl concentration of 1,478 ppm, and the HCl molecular weight of 36.5 lb/lbmole as follows:

$$EF\ (HCl) = (2.67)*(60\ \text{min/hr})*(1{,}478\ \text{ppm}/10^6)*(36.5\ \text{lb HCl/lbmole HCl})*(1\ \text{lbmole}/385\ \text{dscf})$$
$$EF\ (HCl) = 2.24 \times 10^{-2}\ \text{lb HCl emitted per lb waste charged}$$

The general form of the equation used to calculate lb/lb factors for pollutants with concentrations in mg/dscm is as follows:

$$EF = (R) \times (60\ \text{min/hr}) \times (C) \times (m^3/35.3145\ ft^3) \times (\text{lb}/453{,}593\ \text{mg})$$

where:

EF = pollutant emission factor, lb pollutant/lb waste charged
R = ratio of exhaust gas flow rate-to-waste charged, dscfm per lb waste charged per hour [used R = 2.67]
C = average concentration of pollutant, mg/dscm

For example, the Hg emission factor for wet scrubbers is calculated with R = 2.67 and C = 0.131 as follows:

$$EF\ (Hg) = (2.67) \times (60) \times (0.131) \times (1/35.3145) \times (1/453{,}593)$$
$$= 1.31 \times 10^{-6} \text{ lb Hg emitted per lb waste charged}$$

Similar equations are used to calculate the emission factors for pollutants with concentrations in gr/dscf and ng/dscm.

TABLE 1. MWI EMISSION TEST DATA

Type control	Facility	Test	Run	Percent O_2	Waste burned, lb/hr	Gas flow, dscfm at actual O_2	Gas flow, dscfm at 7% O_2	Ratio ft^3/lb/hr
Continuous MWI's								
DS (w/carbon)	Germantown 92	HCl	1	16	1,600	7,130	2,546	1.6
			2	15.6	1,661	6,990	2,696	1.6
			3	15.6	1,668	6,989	2,696	1.6
		Metals	1	15.5	1,445	7,352	2,888	2.0
			2	15.6	1,445	7,259	2,800	1.9
			3	15.1	1,431	6,991	2,946	2.1
DS (w/carbon)	Germantown 91		1	15.2	1,448	7,315	3,031	2.1
			2	15.3	1,447	8,132	3,311	2.3
			3	15.2	1,383	7,982	3,307	2.4
			4	16	1,382	7,920	2,829	2.0
			5	16	1,444	7,859	2,807	1.9
			6	16.1	1,480	7,968	2,789	1.9
			7	15.9	1,481	7,876	2,869	1.9
			8	16.1	1,505	7,795	2,728	2.7
			9	13.5	1,222	6,063	3,248	2.7
			10	16.4	1,485	7,907	2,598	1.7
			11	16.1	1,428	7,770	2,719	1.9
			12	16.2	1,484	7,808	2,677	1.8
			13	16	1,452	7,995	2,855	2.0
DS (w/carbon)	Bronx-Lebanon	HCL	1	15	2,090	6,991	2,953	1.4
			2	14.5	2,124	6,891	3,199	1.5
			3	14.5	1,962	6,691	4,307	2.1
		Metals	1	11.9	2,025	6,626	4,307	2.1
			2	13	2,016	6,578	3,759	1.9
			3	13.1	2,063	6,936	3,914	1.9
DS/FF (w/carbon)	Rochester	Metals	1	12	1,344	3,586	2,305	1.7
			2	12.5	1,174	3,425	2,079	1.8
			3	12.5	1,136	2,966	1,801	1.6
		HCl	1	11.8	1,344	3,855	2,533	1.9
			2	11.6	1,174	3,636	2,441	2.1
			3	12.5	1,174	3,425	2,079	1.8
DI/FF (w/carbon)	Mayo		1	14	1,729	9,118	4,559	2.6
			2	12.8	1,729	9,318	5,458	3.2
			3	14.6	1,729	8,421	3,850	2.2
SD/FF (w/carbon)	M-1-1		1	11.1	723	3,370	2,383	3.3
	M-1-2		2	11.2	734	2,479	1,735	2.4
	M-1-3		3	10.7	789	3,531	2,598	3.3
SD/FF (w/carbon)	M-2-4		4	10.4	663	3,343	2,531	3.8
	M-2-5		5	10.7	638	3,416	2,513	3.9
	M-2-6		6	10.6	716	3,494	2,596	3.6
WS	W. Haven 94	HCl	1	10	851	2,114	1,661	2.0
			2	10.7	869	2,109	1,552	1.8
			3	11.5	834	1,951	1,324	1.6
		Metals	1	10	851	2,122	1,667	2.0
			2	10.7	869	2,045	1,505	1.7
			3	11.5	834	1,904	1,292	1.5
WS	Mass Gen.	Metals	1	12.3	436	2,325	1,445	3.3
			2	12.3	435	2,055	1,277	2.9
			3	12.9	462	2,194	1,269	2.7
		HCl	1	12.5		2,026	1,230	
			2	12.8		2,255	1,321	
			3	13.2		1,924	1,072	
WS	Mercy		1	9.5	958	2,443	2,007	2.1
			2	10	953	2,248	1,766	1.9
			3	9.2	917	2,332	1,966	2.1
WS	St. Vincent		1	7.2		1,575		
			2	9.2		1,829		
			3	8.8		1,689		
WS	Boca '93	HCl	1	10.8	743	2,093	1,525	2.1
			2	10.9	807	2,093	1,510	1.9
			3	11.6	738	2,093	1,405	1.9

TABLE 1. (continued)

Type control	Facility	Test	Run	Percent O_2	Waste burned, lb/hr	Gas flow, dscfm at actual O_2	Gas flow, dscfm at 7% O_2	Ratio ft^3/lb/hr
		Metals	1 2 3	10.8 10.9 11.6	750 750 750	2,217 1,987 2,107	1,615 1,433 1,415	2.2 1.9 1.9
WS	VA Miami		1 2 3	12.1 12.4 11.9	920 920 920	4,428 4,445 4,530	2,815 2,731 2,945	3.1 3.0 3.2
WS	VA Palm Beach	HCl	1 2 3	11.1 11.8 12.1	497 500 498	901 1,034 1,087	637 679 691	1.3 1.4 1.4
		Metals	1 2 3	12.1 11.9 12.1	498 500 498	968 1,065 1,124	615 692 715	1.2 1.4 1.4
WS	JFK	Metals	1 2 3 4	8.9 9 9 9.5	750 750 750 750	2,026 1,873 2,023 1,980	1,751 1,605 1,734 1,626	2.3 2.1 2.3 2.2
		Hg	1 2 3	9.5 8.2 8.9	750 750 750	2,148 1,366 1,526	1,764 1,267 1,319	2.4 1.7 1.8
		PB	1 2 3	11.8 9 8.4	750 750 750	2,260 2,005 2,019	1,485 1,719 1,817	2.0 2.3 2.4
WS	Hershey	HCl	1 2 3	8.8 9.1 8.8	966 1,121 1,037	2,349 2,410 2,517	2,047 2,049 2,193	2.1 1.8 2.1
		Metals	1 2 3	7.7 7.3 7.9	1,048 1,095 923	2,461 2,338 2,375	2,388 2,288 2,222	2.2 2.1 2.4
WS	Boca '94	HCl	1 2 3	8.5 8 8	734 732 737	1,896 1,703 1,743	1,693 1,581 1,619	2.3 2.2 2.2
WS	Bethesda 2/93		1 2 3	13 12.8 12.8		2,705 2,561 2,550	1,546 1,500 1,494	
WS	Univ. of Texas	HCl	1 2 3	9.4 6 7.8	1,355 1,484 1,382	3,013 2,992 3,090	2,496 3,206 2,913	1.8 2.2 2.1

TABLE 1. (continued)

Type control	Facility	Test	Run	Percent O_2	Waste burned, lb/hr	Gas flow, dscfm at actual O_2	Gas flow, dscfm at 7% O_2	Ratio ft^3/lb/hr
Intermittent MWI's								
DI/FF	A-1-1			13	367	1,577	901	2.5
	A-1-2			12	344	1,458	937	2.7
	A-1-3			13.1	386	1,548	874	2.3
	A-2-1			11.7	333	1,285	854	2.6
	A-2-2			11.7	297	1,312	872	2.9
	A-2-3			12	283	1,332	856	3.0
	A-3-1			12	405	1,509	970	2.4
	A-3-3			12.1	414	1,523	968	2.3
	A-3-4			12.3	414	1,585	985	2.4
	A-4-1			10.9	463	1,349	973	2.1
	A-4-2			13.2	405	1,554	866	2.1
	A-5-1			13.1	279	1,536	867	3.1
	A-5-2			13	320	1,508	862	2.7
	A-5-3			12.8	246	1,469	860	3.5
	A-6-1			11.5	344	1,246	846	2.5
	A-6-2			12.3	295	1,365	848	2.9
	A-6-3			11.6	298	1,332	894	3.0
	A-6-4			13.9	321	1,586	894	2.5
	A-7-1			10.7	375	1,474	1,084	2.9
	A-7-2			11.4	299	1,460	1,001	3.3
	A-7-3			11.6	338	1,482	995	2.9
	A-1a-2		2	13.5	404	1,625	871	2.2
	A-1a-3		3	13.8	354	1,824	938	2.6
	A-1a-4		4	14.9	396	1,798	783	2.0
w/carbon	A-8-5		5	14.4	388	1,865	879	2.3
	A-8-6		6	14.3	386	1,829	875	2.3
	A-9-7		7	14.4	414	1,769	834	2.0
	A-9-8		8	14.4	370	1,754	827	2.2
			9	12.9	368	1,660	960	2.6
1/4 sec	Sanford		1	15.76	74	956	358	4.8
			2	15.69	114	863	327	2.9
			3	16.13	83	851	296	3.6
			4	15.16	107	927	387	3.6
			5	15.6	118	971	374	3.2
			6	15.7	101	915	346	3.4
			8	15.5	113	955	375	3.3
			9	15.28	118	996	407	3.5
			10	15.72	70	882	333	4.8
1/4 sec	Kinston	1	1	10.9	154	1,165	840	5.5
		1	2	10.1	175	1,154	898	5.1
		1	3	14.3	206	1,218	583	2.8
		2	4R	14	132	1,137	569	4.3
		2	5R	13.9	137	1,177	597	4.4
		2	6	11.9	133	,102	716	5.4
		3	7	13	186	1,071	612	3.3
		3	8	14.6	207	1,117	511	2.5
		3	9	13.2	200	1,087	606	3.0
1/4 sec	Wilmington	1	1	8.5	123	1,014	905	7.3
		1	5	9.3	135	1,233	1,031	7.6
		1	6	9.8	134	1,212	970	7.2
		2	2	7.2	117	848	836	7.1
		2	3	9.4	148	921	763	5.1
		2	4	7.7	186	1,184	1,125	6.0
		3	7	11.8	208	1,071	704	3.4
		3	8	9.2	203	1,117	941	4.6
		3	9	9	212	1,087	932	4.4
WS	Bayfront	HCl	1	9.1	979	2,520	2,142	2.2
			2	9.8	1,002	2,480	1,984	2.0
			3	10.4	1,010	2,610	1,976	2.0
WS	Stonybrook		1	11.43	707	2,140	1,463	2.1
			2	11.93	718	2,107	1,365	1.9
			3	11.13	796	2,191	1,545	1.9
WS	Rahway	HCl	1	12.66	201	1,433	854	4.3
			2	12.85	217	1,433	834	3.8
			3	12.88	199	1,419	823	4.1
		SO_2	1	12.9		1,435	830	
			2	13.1		1,416	799	
			3	12.8		1,412	827	

TABLE 1. (continued)

Type control	Facility	Test	Run	Percent O_2	Waste burned, lb/hr	Gas flow, dscfm at actual O_2	Gas flow, dscfm at 7% O_2	Ratio ft^3/lb/hr
		Metals	1 2 3	12.5 12.2 13	201 217 199	1,454 1,457 1,469	883 916 839	4.4 4.2 4.2
WS	Memorial City	HCl	1 2 3	10.9 10.8 10	278 272 295	930 894 868	671 651 682	2.4 2.4 2.3
		Metals	1 2 3	11 10.8 10.6	267 296 276	966 871 928	690 635 689	2.6 2.1 2.5
WS	Norwalk	HCl	1 2 3	12.6 12.2 13.5	204 202 198	1,109 897 832	611 564 446	3.0 2.8 2.3
		Pb	1 2 3	14 13.9 13.9	205 207 159	863 827 943	432 419 478	2.1 2.0 3.0
		SO_2	1 2 3	7 7.6 8.5	203 206 188	535 587 513	535 562 458	2.6 2.7 2.4

TABLE 2. POLLUTANT CONCENTRATIONS FOR MWI CONTROL TECHNOLOGIES

Pollutant/units	Pollutant concentrations at 7 percent oxygen					
	Combustion controls			Wet scrubbers	Dry scrubbers, w/o carbon	Dry scrubbers, w/carbon
	1/4-sec	1-sec	2-sec			
CDD/CDF TEQ, ng/dscm	396.4	91.0	7.4	0.79	7.4	0.16
CO, ppm	696.8	297.2	13.04	13.04	13.04	13.04
PM, gr/dscf	0.3	0.16	0.1	a	0.001	0.0025
HCl, ppm	1,478	1,478	1,478	2.328	28.7407	28.7407
Pb, mg/dscm	3.8	3.8	3.8	0.332	0.0131	0.0131
SO_2, ppm	12	12	12	12	12	12
Hg[b], mg/dscm	3.7	3.7	3.7	0.131	3.7	0.166
Cd, mg/dscm	0.41	0.41	0.41	0.046	0.0026	0.0026
NO_x, ppm	121	121	121	121	121	121

[a]Low efficiency: 0.038
Moderate efficiency: 0.014
High efficiency: 0.007
[b]With waste reduction, the concentrations for combustion control and dry scrubber w/o carbon are 1.1 mg/dscm.

TABLE 3. EMISSION FACTORS FOR MWI'S

Pollutant	Emission factors, lb pollutant emitted per lb waste charged						
	Combustion controls			Wet scrubbers	Dry scrubber, w/o carbon	Dry scrubber, w/ carbon	Fabric filter/ packed bed
	1/4-sec	1-sec	2-sec				
TEQ	3.96×10^{-9}	9.09×10^{-10}	7.44×10^{-11}	1.01×10^{-11}	7.74×10^{-11}	1.68×10^{-12}	6.81×10^{-10}
CDD/CDF	1.94×10^{-7}	4.45×10^{-8}	3.65×10^{-9}	4.26×10^{-10}	3.65×10^{-9}	7.04×10^{-11}	3.34×10^{-8}
CO	8.12×10^{-3}	3.46×10^{-3}	1.52×10^{-4}	1.52×10^{-4}	1.52×10^{-4}	1.52×10^{-4}	1.52×10^{-4}
PM							
Batch MWI's	1.81×10^{-3}	9.63×10^{-4}	6.02×10^{-4}	a	2.06×10^{-5}	2.06×10^{-5}	2.06×10^{-5}
Nonbatch MWI's	6.87×10^{-3}	3.66×10^{-3}	2.29×10^{-3}	b	2.29×10^{-5}	2.29×10^{-5}	2.29×10^{-5}
HCl	2.24×10^{-2}	2.24×10^{-2}	2.24×10^{-2}	3.54×10^{-5}	4.37×10^{-4}	4.37×10^{-4}	3.54×10^{-5}
Pb	3.80×10^{-5}	3.80×10^{-5}	3.80×10^{-5}	3.32×10^{-6}	1.31×10^{-7}	1.31×10^{-7}	1.31×10^{-7}
SO_2	3.20×10^{-4}	3.20×10^{-4}	3.20×10^{-4}	3.20×10^{-4}	3.20×10^{-4}	3.20×10^{-4}	3.20×10^{-4}
Hg	3.70×10^{-5}	3.70×10^{-5}	3.70×10^{-5}	1.31×10^{-6}	3.70×10^{-5}	1.66×10^{-6}	1.31×10^{-6}
Cd	4.10×10^{-6}	4.10×10^{-6}	4.10×10^{-6}	4.60×10^{-7}	2.60×10^{-8}	2.60×10^{-8}	2.60×10^{-8}
NO_x	1.51×10^{-3}	1.51×10^{-3}	1.51×10^{-3}	1.51×10^{-3}	1.51×10^{-3}	1.51×10^{-3}	1.51×10^{-3}

[a] Low efficiency: 2.33×10^{4}
Moderate efficiency: 4.12×10^{5}
High efficiency: 4.12×10^{5}
[b] Low efficiency: 8.70×10^{4}
Moderate efficiency: 3.20×10^{4}
High efficiency: 1.60×10^{4}

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